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Introduction to the Special Issue on the

Bay of Bengal: From Monsoons to Mixing

By Amala Mahadevan, Theresa Paluszkiewicz, M. Ravichandran, Debasis Sengupta, and Amit Tandon

The Bay of Bengal has a surprisingly large influence on the world. It nurtures the South Asian summer monsoon, a tremendous ocean-atmosphere-land phenomenon that delivers freshwater to more than a third of the human population on this planet. During summer, southwesterly winds gather moisture from the ocean and carry it deep inland over the Indian subcontinent, bringing welcome rains to a parched land. During winter, the winds reverse to northeasterly, and the ocean circulation responds by dispersing the terrestrial freshwater runoff concentrated in the northern part of the bay. This freshwater impacts the ocean's structure, circulation, and biogeochemistry in numerous ways and, through modification of sea surface temperature, feeds back to influence air-sea fluxes. Because the atmosphere obtains its moisture and heat for convection from the ocean, the interplay between ocean and atmosphere is crucial for the development and sustenance of the monsoon.

The critical dependence of an agrarian economy food production on rainfall makes the prediction of seasonal monsoonal variability of paramount importance to many countries in South Asia. Global climate models are challenged in representing the South Asian monsoon and exhibit large biases over the northern Indian Ocean. Although total rainfall over India during the summer monsoon varies by just about 10% from year to year, the spatiotemporal variability in summer precipitation is large, difficult to predict, and has far-reaching implications for farmers and water management. Intraseasonal wet and dry spells are associated with active and break periods that develop and propagate northward over the Bay of Bengal (Figure 1). Ocean-atmosphere coupled models have greater skill in representing and predicting the prominent intraseasonal oscillations (ISOs) than stand-alone atmospheric models. This highlights the importance of the feedback between the upper-ocean structure and air-sea interaction on ISO time scales.

The introduction of coupled climate models has brought the ocean's role in ISOs to light and has led to considerable improvement in monsoon prediction. But further work is needed for forecasting the short- to medium-range variability of monsoon rainfall. The skill of ISO prediction is still modest compared to its potential, giving reason to strive for longer lead times to improve forecast accuracy. The ocean component of coupled models has particular difficulty in representing the Bay of Bengal as compared to other ocean regions, likely because the bay is different from other oceans in many ways. The Bay of Bengal and surrounding land areas receive the heaviest rainfall in the world, and the bay's surface waters are the freshest of any tropical ocean. The strong, seasonally reversing winds affect the circulation, with cyclones developing over the bay's warm waters during both the pre- and post-monsoon seasons. With

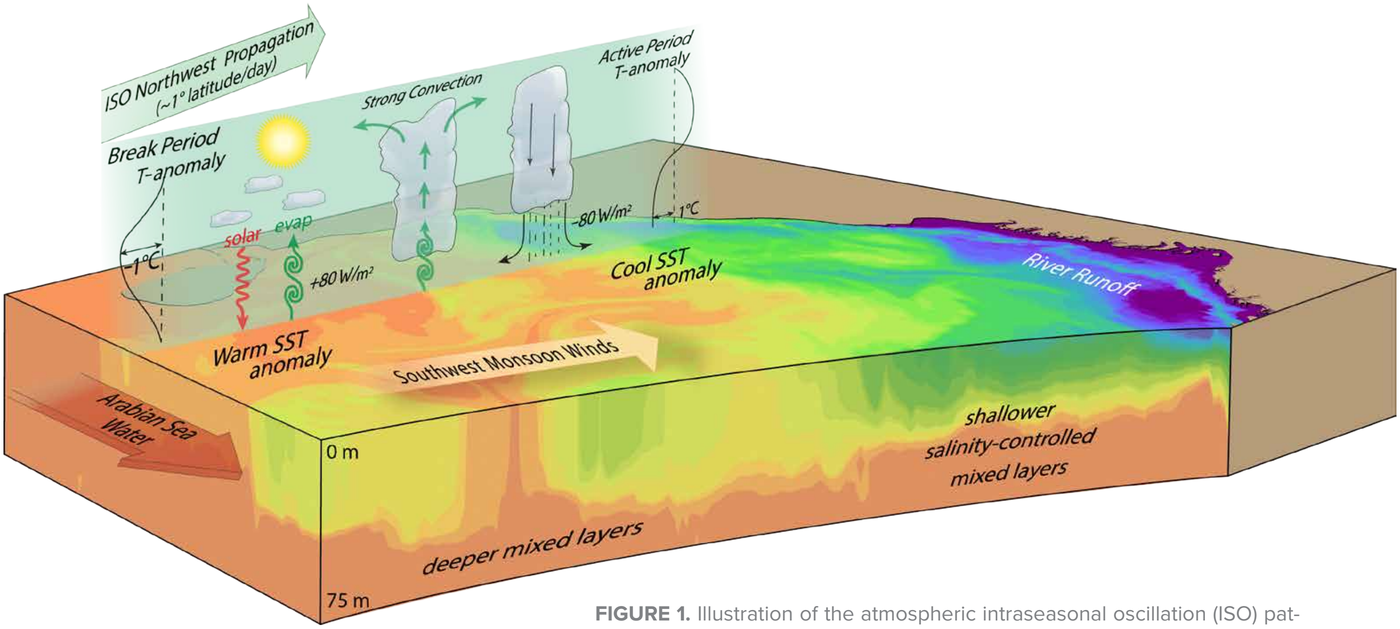

FIGURE 1. Illustration of the atmospheric intraseasonal oscillation (ISO) pattern that propagates over the Bay of Bengal during the southwesterly monsoon season. Color in the ocean represents salinity, and was produced using the HYbrid Coordinate Ocean Model, or HYCOM (Cummings and Smedstad, 2013, http://dx.doi.org/10.1007/978-3-642-35088-7_13). *Schematic drawing by Emily Shroyer and produced by David Reinert, Oregon State University.*

the Indian subcontinent to its north, the ocean lacks a place where dense waters can form from surface cooling and cause overturning. The freshwater at the northern end of the bay offsets the effect of cooling by northeasterly winds and suppresses vertical mixing.

Better characterizations of the structure and processes in the Bay of Bengal are needed to improve the representation of its role in the monsoons. This was the primary motivation for an international collaboration between Office of Naval Research (ONR)-sponsored scientists from the United States and Ministry of Earth Sciences (MoES)-sponsored scientists in India, and further, between ONR-sponsored scientists and colleagues from the National Aquatic Research Agency (NARA) in Sri Lanka. These scientific teams set out to improve understanding of the Bay of Bengal through observations and process modeling studies. Three concurrent programs were launched: ONR's Air-Sea Interactions Regional Initiative (ASIRI), MoES's Ocean Mixing and Monsoon (OMM) project under the umbrella of India's Monsoon Mission, and NARA's Coastal Circulation Studies in collaboration with US Naval Research Laboratory scientists under the Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon (EBOB) study. This set of complementary and coordinated programs brought an international team of scientists together to better understand the Bay of Bengal's processes and role in air-sea interaction, and its circulation and transport.

These programs led to several observational campaigns that have provided a wealth of new understanding about the bay. Modeling studies were used to synthesize the information collected, to quantify transports, and to extend our understanding of processes at work in the bay. The observations began in 2013 with two US Research Vessel (R/V) *Roger Revelle* cruises to the north and south bay during November–December, and a cruise of the Indian Ocean Research Vessel (ORV) *Sagar Nidhi* to the north bay (Figure 2). Six current moorings were deployed from R/V *Roger Revelle* in the south central Bay of Bengal in December 2013 for a period of 20 months. In 2014, *Revelle* sailed from Chennai, India, and sampled the central Bay of Bengal during June, the early part of the summer monsoon; later in the season, *Sagar Nidhi* made observations in the northern Bay of Bengal in August–September. The summer monsoon of 2015 was the intensive observational period, when *Revelle* and *Sagar Nidhi* conducted joint research in the northern bay. A highly instrumented surface mooring was deployed in December 2014 from *Sagar Nidhi* and retrieved in February 2016. Gliders surveyed the southern and central bay, moorings were used to profile vertically, and surface drifters tracked circulation. Satellite data from NASA's Aquarius and SMAP (Soil Moisture Active Passive) missions and the Indian SARAL (Satellite

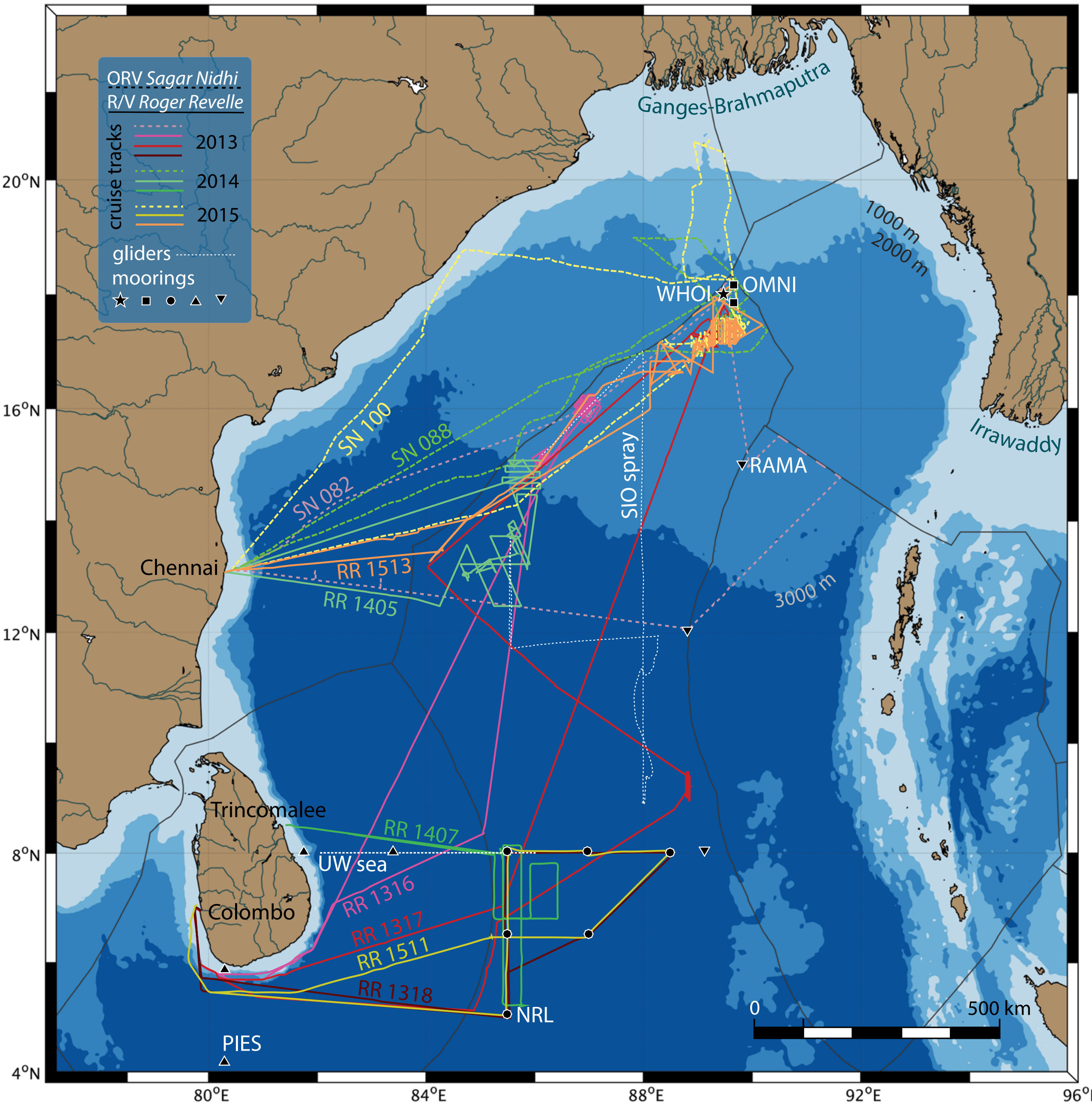

FIGURE 2. Map of the Bay of Bengal. Colored lines show 2013–2015 tracks of R/V *Roger Revelle* (RR, solid lines) and ORV *Sagar Nidhi* (SN, dashed lines) during cruises for the Air-Sea Interactions Regional Initiative (ASIRI), the Ocean Mixing and Monsoon (OMM) project, and Effects of Bay of Bengal Freshwater Flux on Indian Ocean Monsoon (EBOB) program. Black and white symbols indicate positions of various surface and subsurface moorings deployed or utilized as part of the research campaigns. NRL = Naval Research Laboratory. OMNI = Ocean Moored Network of buoys for the Northern Indian Ocean. PIES = Pressure Inverted Echo Sounder. RAMA = Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction. WHOI = Woods Hole Oceanographic Institution. White dotted lines are tracks of gliders. UW sea = University of Washington Seaglider. SIO spray = Scripps Institution of Oceangraphy spray glider. Major riversheds are named along with ports of call. Thin black lines demarcate national Exclusive Economic Zones. *Map created by Gualtiero Spiro Jaeger, MIT/WHOI Joint Program.*

with ARgos and ALtiKa) and INSAT-3D missions, combined with information from other satellites, were analyzed and used to provide context to the studies. The Sri Lankan R/V *Samudrika* surveyed coastal currents, hydrophysical fields, and mixing rates off the south and east coasts of Sri Lanka. Several current moorings and inverted echosounders were also deployed east and south of Sri Lanka to examine seasonally varying boundary currents.

The collaborative effort led to several technical and observational breakthroughs. The ship surveys, including a multi-vessel international operation, provided unprecedented horizontal and vertical resolution of the Bay of Bengal. New technologies for autonomous sampling contributed a detailed view of the near-surface structure. A year-long time series of surface and upper-ocean variables, at high vertical resolution, provided data that accurately quantifies air-sea fluxes of heat, moisture, and momentum. A glider deployed from *Sagar Nidhi* surveyed a small region of the ocean around the mooring in the period September to December 2015. In addition, moorings in the southern bay recorded subsurface currents that were hitherto unseen.

The sharing of scientific methodology, findings, and data was achieved through several forums—summer schools, joint workshops and training activities, and special sessions at international conferences. These efforts thrived through collaboration between the countries, multiple institutions, numerous scientists, students, technicians, and ships' crew. Some of the findings that have emerged from this fruitful endeavor over the past five years are presented in this special issue of *Oceanography*. More detailed findings will continue to be reported in other journals.

The articles that follow present a new understanding of the Bay of Bengal, the observed air-sea exchange of heat and momentum, the structure of salinity and temperature, and rates of mixing, transports, and circulation. Sustained measurements at the sea surface, as well as satellite data, enhance understanding of air-sea interaction, as shown here. The biases of climate models in the bay suggest the need to represent processes crucial for maintaining the freshwater stratification.

Abundant freshwater makes the Bay of Bengal unique, and more akin to the Arctic than to other tropical regions. Strong lateral salinity gradients lead to a multitude of fronts that give rise to a host of instabilities over a range of spatial and temporal scales. Strong vertical gradients and fine-scale salinity and temperature structures are reflected in the layered density stratification. Freshwater stratification thereby influences how the temperature of the upper ocean responds to penetrative solar radiation and latent and longwave cooling on seasonal and diurnal time scales.

Microstructure measurements reveal that rates of diapycnal mixing beneath the surface mixed layer are very weak, even in the presence of the southwest monsoon winds, and even though inertial motions and internal tides provide a strong source of vertical shear. Biogeochemical properties also respond to the stratification and have strong vertical gradients, to which the phytoplankton and faunal communities respond.

At a larger scale, the water mass characteristics of the Bay of Bengal differ significantly from those of the Arabian Sea, and the bay's properties are set by both the rate of freshwater input and the circulation that exchanges salinity between the Bay of Bengal and the tropical Indian Ocean. The circulation and freshwater transport are estimated from drifters, moorings, gliders, and models. This large-scale circulation affects the salinity gradients and the host of smaller-scale instabilities that set the stratification and fine-scale structure in the bay.

The studies described in this special issue give the world a first high-resolution view of the Bay of Bengal's ocean structure. But these initial studies raise new questions and challenges. One that looms in importance is that of understanding the coupled ocean-atmosphere feedback on the subseasonal, 10–60 day time scale. This interaction lies at the heart of the active and break cycles that constitute monsoon variability and that beg understanding for improving weather predictions.

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AUTHORS

Amala Mahadevan (amala@whoi.edu) is Senior Scientist, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. **Theresa Paluszkiewicz** is Program Officer, Office of Naval Research, Arlington, VA, USA. **M. Ravichandran** is Head, Observations and Modeling at the Indian National Centre for Ocean Information Services, Hyderabad, India. **Debasis Sengupta** is Professor, Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India. **Amit Tandon** is Professor of Mechanical Engineering, University of Massachusetts Dartmouth, North Dartmouth, MA, USA.

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